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AN ORTHOGONAL LINE ARRAY OF DIRECTIONAL CLASS IV FLEXTENSIONAL TRANSDUCERS

Dennis F. Jones — Stephen C. Butler — Jan F. Lindberg

Defence Research Establishment Atlantic

Centre de Recherches pour la Défense Atlantique

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Approved by: R.H. Kawahara:
Head / Electromagnetics Section

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Abstract

Acoustic monopoles and the principle of superposition (applied to sound pressure) are fundamental tools that can be used to construct theoretical dipole and cardioid sound sources. Strictly speaking, the size of these monopoles, and their separations when forming simple multipoles like dipole doublets, must be small compared to the wavelengths emitted. In the practical field of sonar transducer design, however, transduction devices have finite dimensions, and consequently, do not meet the basic size and separation criteria for their transmissions to be accurately described by those of multipole sources. Nevertheless, there are transducers that produce good approximations to the omnidirectional, bidirectional, and unidirectional radiation patterns of monopole, dipole, and cardioid sources, respectively. One such device is the low-frequency (900 Hz) directional Class IV flextensional transducer. A single element alone can produce omnidirectional, dipole, and left/right cardioid patterns. This unique capability provides the array designer with many options for generating directional beams, compared to arrays composed solely of omnidirectional sources. In this work, the directivity patterns of a single Class IV element and a four-element orthogonal array are presented. A simple theoretical expression based on multipole sources and the principle of superposition is put forward to qualitatively explain all of the measured patterns. [Work supported in part by the Office of Naval Research]

Résumé

Les monopôles acoustiques et le principe de superposition (appliqué à la pression sonore) sont des outils de base qui peuvent être utilisés pour construire des sources sonores dipôles et cardioïdes théoriques. À strictement parler, la taille de ces monopôles et leurs espacements lorsqu'ils forment des multipôles simples, par exemple des doublets, doivent être petits par comparaison aux longueurs d'onde émises. Cependant, dans le domaine concret de la conception des transducteurs sonars, les dispositifs transducteurs ont des dimensions finies, de sorte qu'ils ne satisfont pas aux critères fondamentaux de taille et d'espacement requis pour que leurs émissions soient décrites avec exactitude par celles des sources multipôles. Néanmoins, il existe des transducteurs qui donnent de bonnes approximations des diagrammes de rayonnement omnidirectionnels, bidirectionnels et unidirectionnels des sources monopôles, dipôles et cardioïdes, respectivement. Mentionnons à titre d'exemple le transducteur flextensionnel directif de classe IV à basse fréquence (900 Hz). Un élément simple peut à lui seul produire des diagrammes omnidirectionnels, dipôles et cardioïdes gauche/droite. Cette capacité unique donne au concepteur de réseaux un grand nombre d'options pour la génération de faisceaux directionnels, comparativement aux réseaux composés uniquement de sources omnidirectionnelles. Dans le présent travail, les diagrammes de directivité d'un élément unique de classe IV et d'un réseau orthogonal à quatre éléments sont décrits. Une expression théorique simple basée sur des sources multipôles et sur le principe de superposition est établie en vue d'expliquer qualitativement tous les diagrammes mesurés. [Travail subventionné en partie par l'Office of Naval Research.]

Executive Summary

Report Number:
DREA Technical Memorandum 98/232

Title:
An Orthogonal Line Array of Directional Class IV Flextensional Transducers

Authors:
Dennis F. Jones, Stephen C. Butler, and Jan F. Lindberg

Background:
Recently, D. Jones from the Defence Research Establishment Atlantic (DREA) and S. Butler and J. Lindberg from the Naval Undersea Warfare Center (NUWC) completed a joint underwater acoustical evaluation of low-frequency directional Class IV flextensional transducers and arrays at the NUWC Seneca Lake Facility in New York. Four TR-1426 transducers, belonging to NUWC (Newport, RI) and manufactured by Massa Products Corporation (Hingham, MA), were tested singly and in line array configurations under the auspices of an ONR321SS task for acoustic projector development. Some of the results are reported in this paper.

Results:
It was shown that both a single directional Class IV transducer element and a four-element orthogonal array can produce omnidirectional, bidirectional (dipole), and unidirectional (cardioid) radiation by choosing the correct combinations of input drive voltages and phases. Since a single element can transmit left and right cardioids, the orthogonal array, due to its geometric configuration, can transmit a directional beam in as many as eight directions (i.e., every 45°). As well, at 900 Hz, the orthogonal array should be capable of generating source levels exceeding 220 dB//1μPa-m.

Significance:
For the same resonance frequency, the directional Class IV flextensional transducer is smaller and less massive than non-flextensional transducer designs such as the free-flooded ring. In addition, this transducer can generate omnidirectional, bidirectional, and unidirectional beams without the use of baffles. Switching between beam types is accomplished by electronic control. The use of an array of these transducers could eliminate the need for directional receiving arrays.

Future Plans:
Areas of interest for further investigation include simultaneous left/right transmission at two different frequencies, vertical directivity patterns on the orthogonal array, optimization of the 45° array beams, and high power performance and interaction effects for the array.

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1. Introduction

Flextensional transducers have a history that dates back to the 1920s when these sound sources were primarily used in aeroacoustics applications [1]. Some of the early transducer designs were constructed with dimensions that permitted the generation of directional sound beams, which could be enhanced by placing the transducers inside reflectors of suitable geometries [2]. In air, this approach to achieving directivity is straight forward since it is often possible to make at least one dimension of a flextensional transducer larger than the wavelength of the sound generated at the air-loaded flexural resonance frequency. On the other hand, when a flextensional transducer is designed for underwater operation, all dimensions are generally much smaller than a wavelength and the resulting radiation is omnidirectional. For example, the Class I barrel-stave flextensional projector developed at the Defence Research Establishment Atlantic (DREA) [3, 4] is larger than a wavelength at its air-loaded flexural resonance (1580 Hz) but is more than six times smaller than a wavelength at its water-loaded flexural resonance (830 Hz).

One technique that can be used to create a directional beam of sound with a low-frequency, omnidirectional, underwater flextensional transducer is to mount the transducer in front of a rigid baffle. Unfortunately, whereas the aeroacoustic reflectors were relatively small enclosures, low frequency underwater baffles are very large, massive, and costly structures that are not practical for most modern sonar applications. A more technologically viable method for achieving directivity from omnidirectional flextensional transducers is to use two vertical line arrays separated by a quarter wavelength and phased in quadrature [5]. Such a directional two-line array consisting of four flextensional transducers is briefly reviewed in Section 2.

Ten years ago, a novel idea for producing directional radiation from a single Class IV flextensional transducer was put forward by Butler [6]. At the heart of the concept was an internal driver that could be excited into either longitudinal vibrations that produced the usual fundamental flexural shell mode, or bending vibrations that gave rise to a rigid-body translational shell mode. There were skeptics who believed that such a concept was breaking the laws of physics [7], however, the coup de grâce came in the form of a directional 3.25 kHz Class IV flextensional transducer prototype that was approximately three times smaller than the wavelength of sound produced [8, 9]. The initial reduction to practice was the result of a Naval Undersea Warfare Center (NUWC) Small Business Innovation Research (SBIR) program contract to Massa Products Corporation resulting in the Model TR-1420, which employed a Class IV aluminum oval shell supplied by British Aerospace. This directional transducer presented an opportunity to replace the previously mentioned two vertical line arrays of omnidirectional transducers by a single line array of directional transducers. Of course, the obvious advantages are significant array size and weight reductions plus associated cost savings.

By 1995, a number of 900 Hz Class IV directional flextensional transducers (Model TR-1426) were under development at Massa Products for the purpose of building a single vertical line array capable of transmitting left/right [10]. The acoustic performance was reported by Butler et al. [11] in 1997 for both a single element and a six-element line array. Recently, a novel four-element line array configuration was assembled and tested jointly by DREA and NUWC using four TR-1426 transducers and the results are the subject of this paper. A simple simulation procedure for the directivity patterns of interest is put forward in Section 3. Single element and four-element array measurements are given in Sections 4 and 5 respectively.

2. Existing Directional Technology

It is useful to compare the performances of a single directional Class IV flextensional transducer (Section 4) and a line array of these directional transducers (Section 5), with the

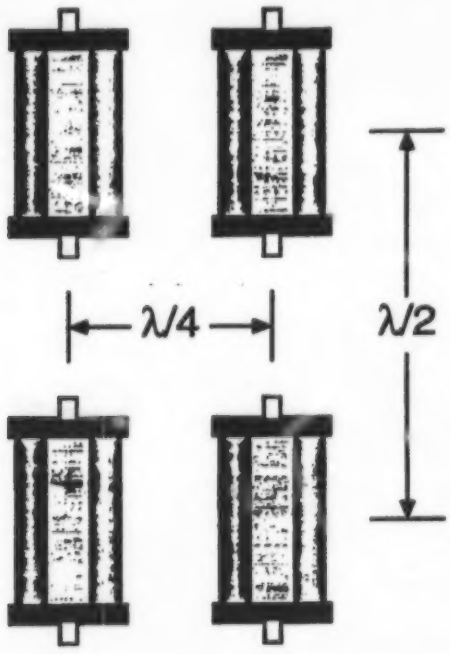

Figure 1: Conventional directional array.

current technology for generating directivity with omnidirectional flextensional transducers. Therefore, the acoustic performance of a German active towed array sonar (ATAS) concept demonstrator is briefly reviewed here [5].

The ATAS array configuration consisted of two vertical lines of flextensional transducers as shown in Fig. 1. For illustrative purposes, the transducers shown in the figure represent Class IV flextensionals (British Aerospace Model WAB506) as viewed from the side, although Class V ring-shell flextensional transducers (Sparton of Canada Model 18A0950) were also used. In this configuration, the two lines of transducers were spaced a quarter wavelength apart and were driven 90° out of phase in order to create cardioid beam patterns either left or right. Furthermore, the top elements were separated from the bottom elements by half a wavelength to reduce the fathometer effect by creating nulls above and below the array.

At 950 Hz, near the fundamental flexural resonance frequency of a single element, the four-element array produced left and right cardioid beams with a maximum source level of 217 dB//1μPa-m and a left/right ratio of 15 dB. The test depth of the array was not specified, however, it was stated that the measurements were performed in a deep-water Norwegian fjord.

3. Pattern Simulations

All of the measured directional plots in the following two sections are based on monopole and/or dipole directivity patterns. For example, the linear superposition of omnidirectional and dipole patterns produces a cardioid pattern, while two orthogonal dipole patterns produce another dipole pattern rotated by 45°. Consequently, the generalized angular dependence of the acoustic pressure amplitude $P(\theta)$ can be represented by the following expression,

$$P(\theta) \propto |C_1 + C_2 \cos(\theta) + C_3 \sin(\theta)|, \quad (1)$$

where C_1, C_2, and C_3, are constants whose values determine the shapes of the patterns. Equation (1), which can be written in decibel form if desired, is merely intended to be an aid to visualization and is not used to fit the data in this work since no new information would be forthcoming. Hence, the values for the three constants are given for each pattern in the next two sections so that the reader can make similar plots using a scientific graphic calculator or plotting software on a personal computer. Three examples are as follows: (C_1, C_2, C_3)=(1, 0, 0) yielding an omnidirectional pattern, (C_1, C_2, C_3)=(0, 1, 0) yielding a dipole pattern, and (C_1, C_2, C_3)=(1, 1, 0) yielding a cardioid pattern. All graphical simulations are presented in the Appendix.

4. Single Element Measured Results

Figure 2 shows a sketch of the Massa Products Model TR-1426 Class IV directional flextensional transducer and indicates its approximate dimensions. The transducer is driven by an internal piezoceramic driver and has an overall mass of 147.4 kg. The main radiating surfaces of the oval shell are labelled A and B. These labels are also used for the internal bender bar driver whose two sides are electrically isolated from each other and wired separately. The longitudinal and bending excitations of this driver produce quadrupole and dipole modes of vibration, and when both modes are excited, a cardioid pattern is produced. Details on the construction and theory of operation of this transducer are given by Butler et al. [11].

4.1 Quadrupole Mode

The quadrupole vibrational mode for a Class IV flextensional transducer is the fundamental flexural mode that arises by driving an oval shell along its major axis. As the ends of the oval move outward with the expanding piezoceramic driver, the lateral surfaces of the oval move inward. Since the end and lateral surfaces are out of phase, four nodal points exist near the ends and the mode shape is quadrupolar. Furthermore, since the lateral surface areas are much larger than the end surface areas, the far-field radiation pattern is essentially omnidirectional.

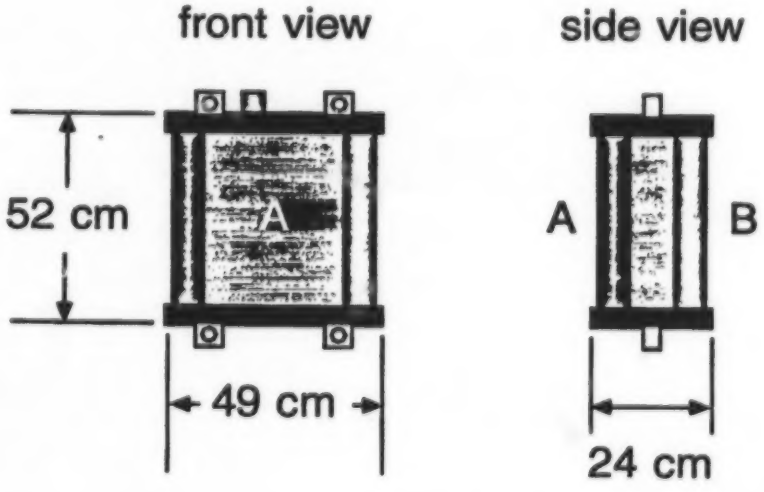

Figure 2: Single element dimensions.

The quadrupole mode is excited by driving both sides of the internal piezoceramic stack (i.e., A and B) with equal voltage amplitudes and phases. Therefore, the ratio of the complex drive voltages, E_A and E_B, is given by

$$\frac{E_A}{E_B} = 1 @ 0°. \tag{2}$$

A Class IV directional transducer was tested at the U.S. Naval Undersea Warfare Center's Seneca Lake Facility in New York. The electroacoustic performance results for this transducer, operating in the quadrupole mode, are presented here. The transducer was submerged to a depth of 61 m in freshwater where the measured sound speed was 1426 m/s. The transducer was driven with a low voltage drive of 300 Vrms corresponding to an electric field of about 470 Vrms/cm (1.2 Vrms/mil). The measured electrical conductance and susceptance curves for the Class IV transducer driven in its quadrupole mode and using the drive condition of Eq. (2), are shown in Fig. 3. The peak in the conductance curve indicates a resonance frequency of 850 Hz and a -3 dB mechanical quality factor of 3.5.

In order to calculate the complex drive voltage ratio for the directional beam in Subsection 4.3, for a given frequency, it is necessary to measure the acoustic phase response and transmitting voltage response (TVR). These curves are shown in Figs. 4 and 5. The phase angle and TVR at resonance are –76° and 142 dB//1μPa-m/V, respectively. The calculated field-limited source level, at the traditional established nominal field level of 3.94 kVrms/cm (10 Vrms/mil), is 210 dB//1μPa-m at resonance. The dip in the TVR curve at 700 Hz results from a spurious resonance associated with the end plates.

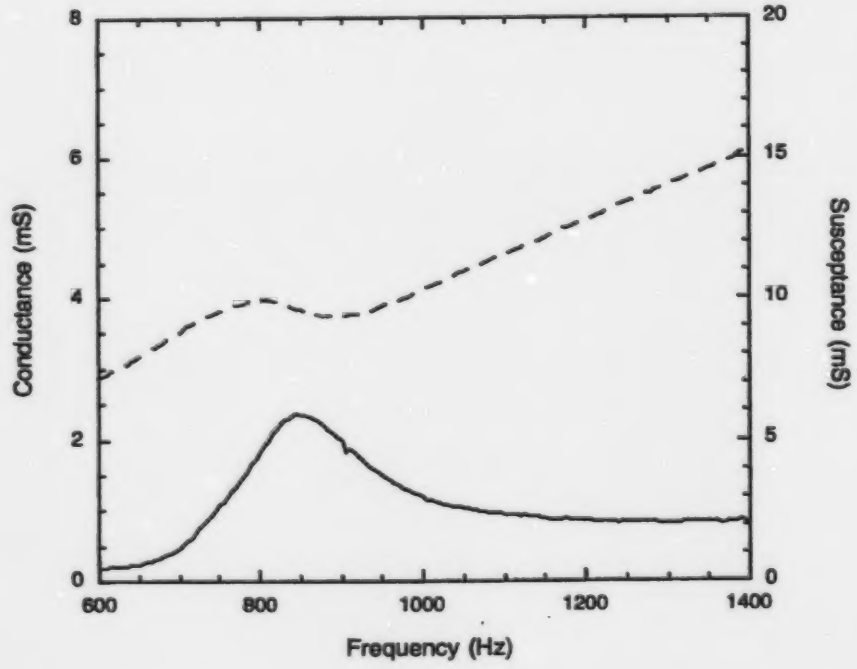

Figure 3: Conductance (solid) and susceptance (dashed) for the quadrupole mode.

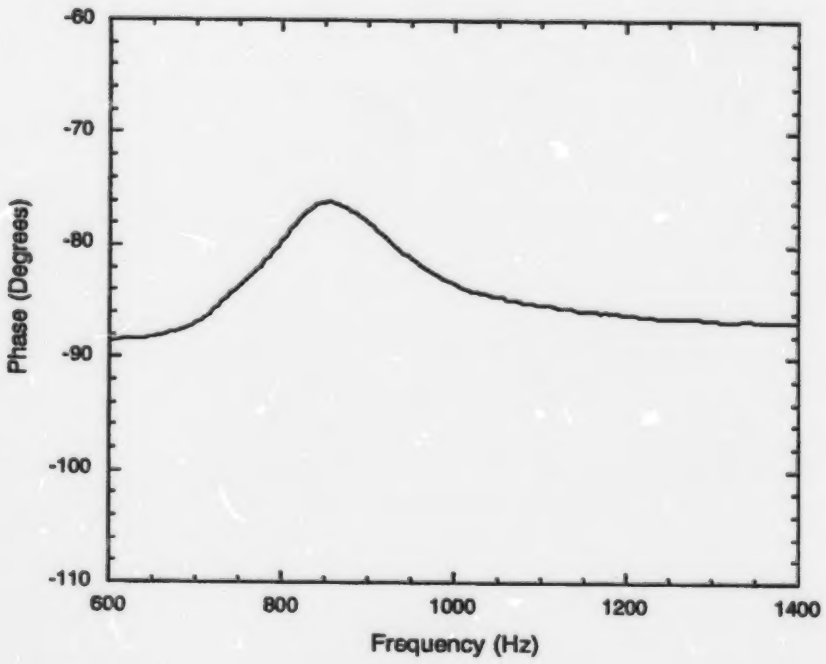

Figure 4: Acoustic phase response for the quadrupole mode.

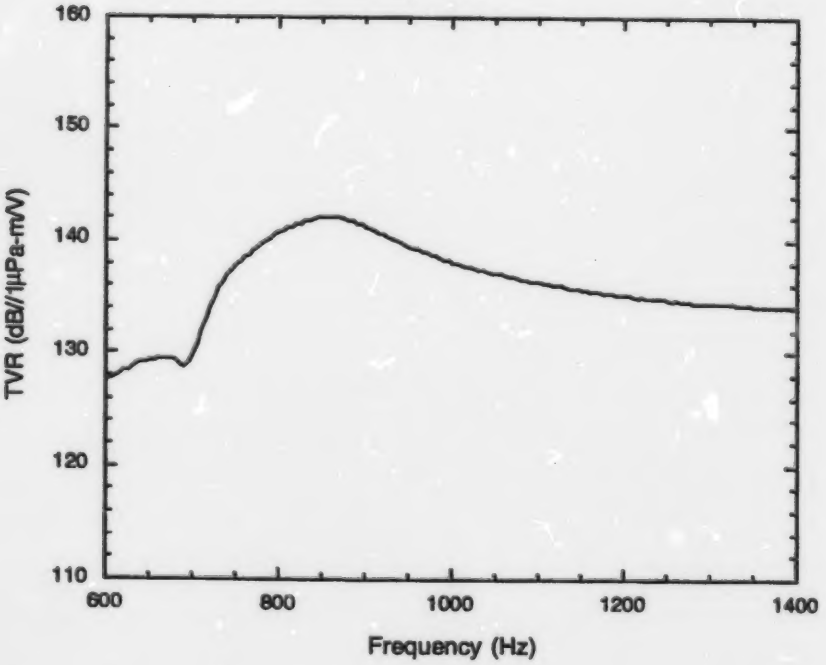

Figure 5: Transmitting voltage response for the quadrupole mode.

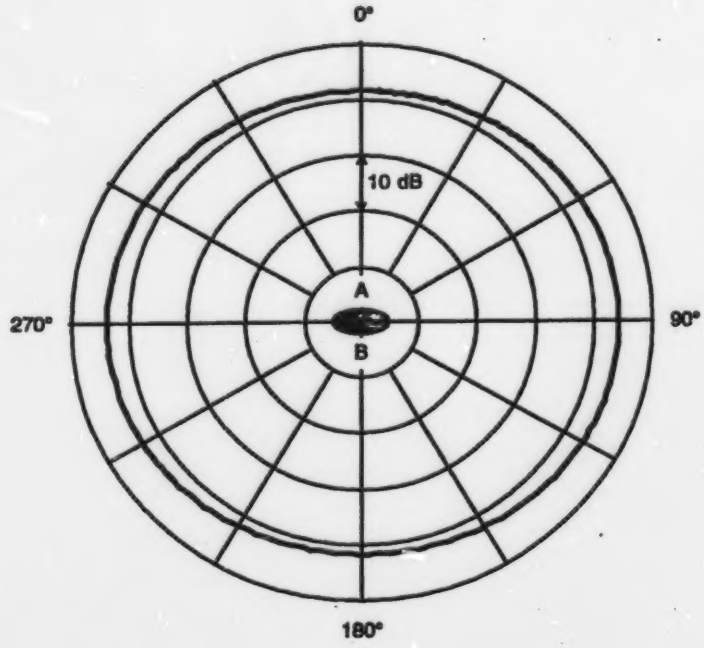

Figure 6: Horizontal directivity pattern for the quadrupole mode at 850 Hz.

At resonance, the measured horizontal directivity pattern is nearly omnidirectional as shown in the polar plot of Fig. 6. This pattern can be simulated by Eq. (1) using (C_1, C_2, C_3)=(1, 0, 0) (see Fig. A1). The transducer orientation is indicated by the gray oval with the A side of the transducer facing 0°. Note that the sound pressure levels at 0° and 180° are about 2.3 dB lower than those at 90° and 270°. This deviation from perfect omnidirectionality is a direct result of path length differences between the ends and sides of the transducer. As we will see in Section 5, the four-element orthogonal array eliminates this deviation.

4.2 Dipole Mode

When the driver is excited into its bending mode, the surrounding shell is translated back and forth in a rigid body motion. The resultant radiation pattern is dipolar in shape with the two lobes 180° out of phase with each other. This dipole mode is obtained by applying the following ratio of complex drive voltages to the driver:

$$\frac{E_A}{E_B} = 1 @ 180°. \tag{3}$$

The measured electrical conductance and susceptance curves are given in Fig. 7. The resonance frequency, obtained from the conductance curve peak, is 880 Hz, which is only 30 Hz higher than the resonance frequency for the quadrupole mode. This small difference in the mode frequencies simplifies the excitation of the directional mode. The –3 dB mechanical quality factor is 16.7; much higher than 3.5 for the quadrupole mode since the radiation impedance is higher for the latter mode.

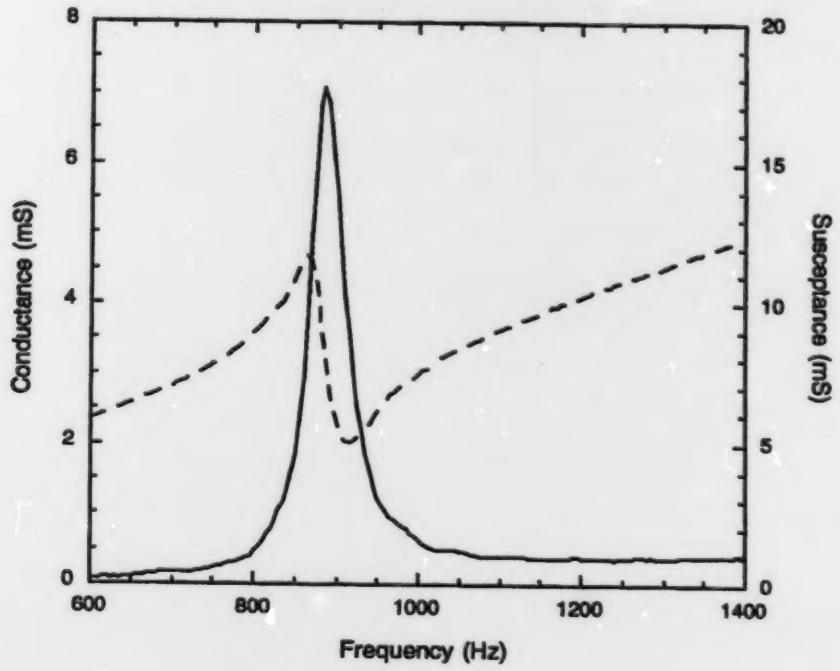

Figure 7: Conductance (solid) and susceptance (dashed) for the dipole mode.

The phase and TVR curves for the dipole mode are shown in Figs. 8 and 9 and their values at resonance are –51° and 152 dB//1μPa-m/V, respectively. The calculated field-limited source level is 220 dB//1μPa-m. The measured horizontal directivity pattern is shown in Fig. 10 and the dipole shape is clearly evident. The simulation of this dipole pattern can be accomplished using Eq. (1) and (C_1, C_2, C_3)=(0, 1, 0) (see Fig. A2).

4.3 Directional Mode

For a given frequency, the complex drive ratio for pressure cancellation, and consequently the generation of a directional cardioid beam, can be calculated from

$$\frac{E_A}{E_B} = \frac{\left(1 + TVR_q / TVR_d\right)}{\left(1 - TVR_q / TVR_d\right)}, \tag{4}$$

where TVR_q is the complex transmitting voltage response (TVR and phase) for the quadrupole mode and TVR_d is the complex transmitting voltage response (TVR and phase) for the dipole mode [11]. If the TVR is not identical on both the A and B sides of the transducer, then separate calculations must be made for the left and right cardioids.

The calculation, using values from Figs. 4, 5, 8, and 9 at 900 Hz, plus manual adjustments of voltage amplitude and phase to find the deepest null, yielded the following condition for directionality

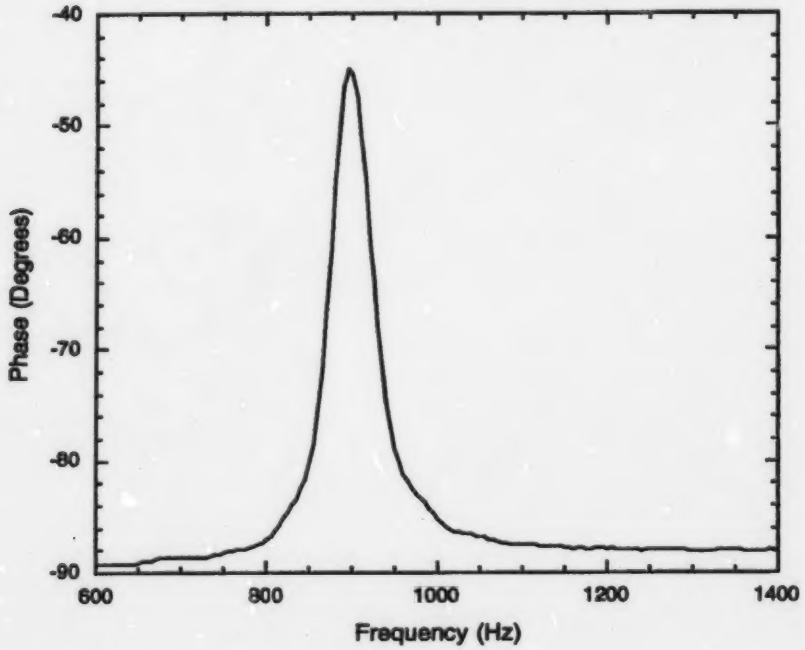

Figure 8: Acoustic phase response for the dipole mode.

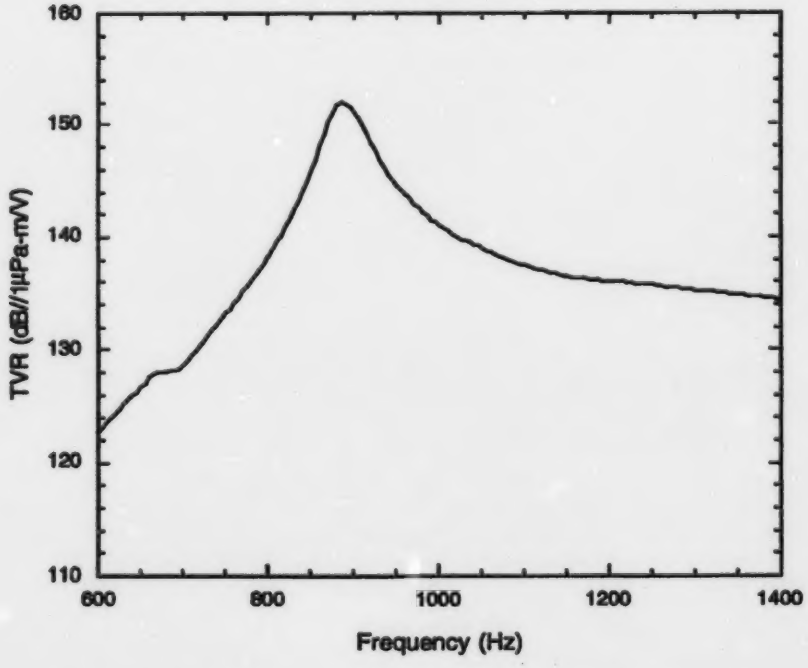

Figure 9: Transmitting voltage response for the dipole mode.

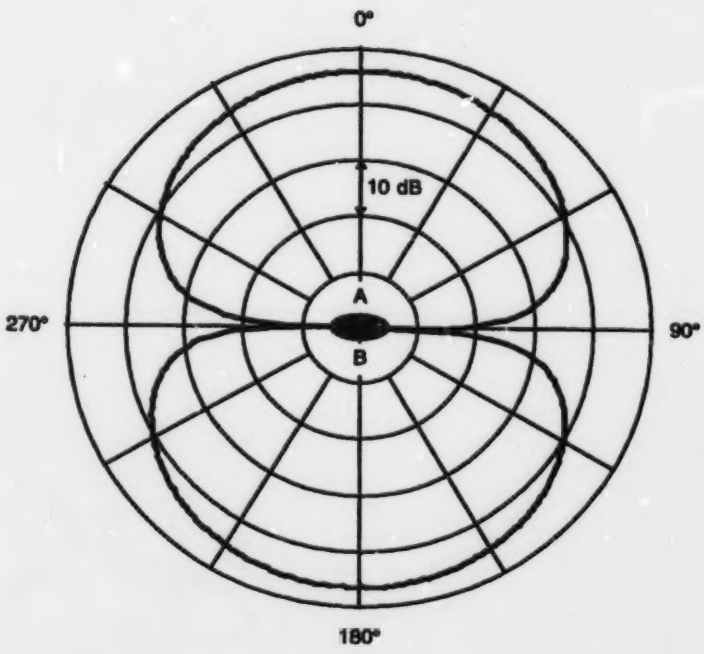

Figure 10: Horizontal directivity pattern for the dipole mode at 850 Hz.

$$\frac{E_A}{E_B} = 1.2 \angle -34°. \tag{5}$$

Figure 11 shows the resultant measured cardioid in the 180° direction. Simply reversing the leads steers the measured cardioid in the opposite direction as shown in Fig. 12. The small backlobe, which is a common feature in directional cardioid patterns [5], is an indication that the transducer is not perfectly symmetric from side A to side B with respect to the TVR levels and phases. Although the TVR was not measured on both sides of the other three transducers and there were asymmetries observed. The calculated field-limited source level at the maximum radiation axis (180° in Fig. 11) is 214 dB//1μPa-m, which has been verified experimentally [11]. The left/right ratio for the cardioid in Fig. 11 is 44 dB. The simulation of the cardioid pattern in Fig. 11 can be accomplished using Eq. (1) and (C_1, C_2, C_3)=(1, -1, 0) while the simulation of the cardioid pattern in Fig. 12, including the backlobe, can be accomplished using Eq. (1) and (C_1, C_2, C_3)=(0.8, 1.2, 0) (see Fig. A8).

The performance of the single directional Class IV transducer presented above compares well with that of the four-element ATAS array presented in Section 2 (cf. 950 Hz resonance frequency, 15 dB left/right ratio, and 217 dB//1μPa-m source level).

5. Orthogonal Array Measured Results

Directional Class IV transducers offer the sonar array designer many options for tailoring acoustic beam patterns from compact geometrical configurations. In order to evaluate the acoustical versatility of a simple array of directional transducers, an orthogonal vertical line of

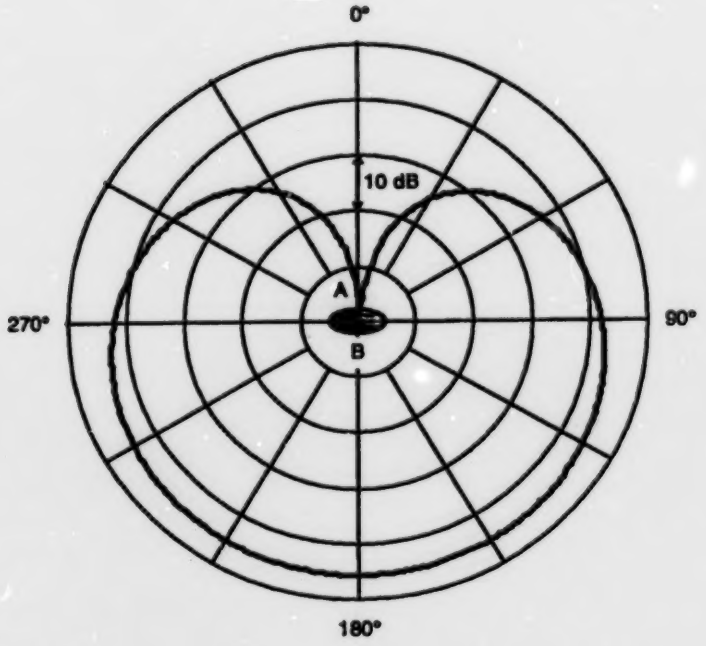

Figure 11: 900 Hz horizontal directional beam steered left.

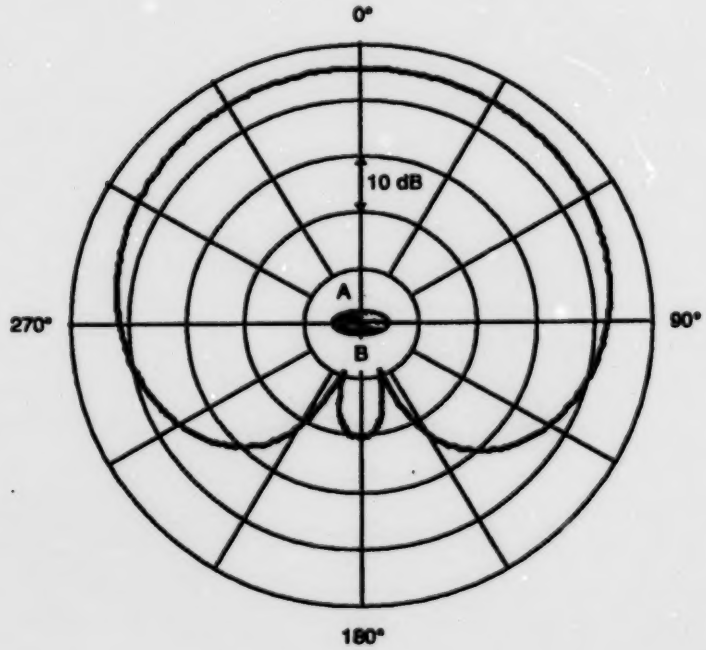

Figure 12: 900 Hz horizontal directional beam steered right.

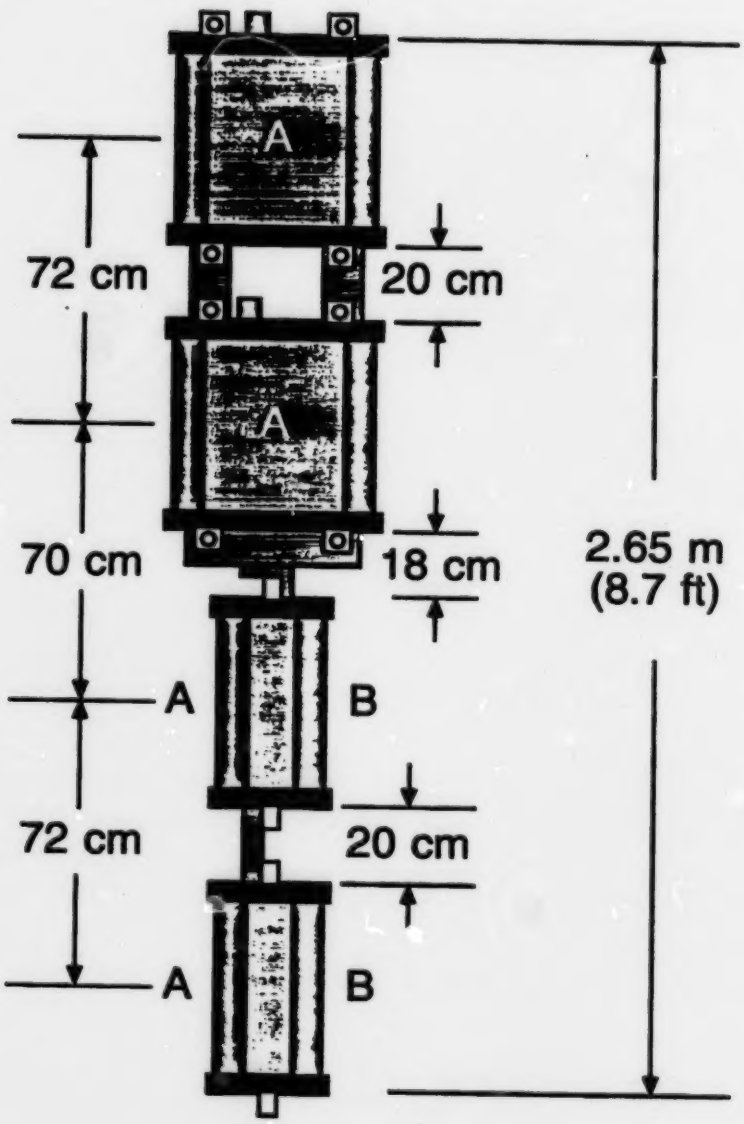

Figure 13: Orthogonal array configuration.

four elements was assembled as shown in Fig. 13. The bottom two elements were oriented at an angle of 90° with respect to the top two elements. The spacing between the centers of the top two elements is 72 cm or 0.45λ at 900 Hz. The bottom two elements have this same spacing. The spacing between the orthogonal pairs of elements is 70 cm or 0.44λ at 900 Hz. The overall length of the array was 2.65 m. The transducer elements were excited with a low 300 Vrms drive and the center of the array was submerged to a water depth of 70 m on a rotating station to facilitate the measurement of directivity patterns.

In this section, we present the measured horizontal patterns produced by simultaneously exciting two or four elements. First of all, two elements were used to create a cardioid by driving one element in its quadrupole mode and the other in its dipole mode (Subsection 5.1). Secondly, four cardioids were formed by driving adjacent pairs of elements in their directional modes (Subsection 5.2). Finally, Subsections 5.3, 5.4, and 5.5 involve the excitation of all four elements in their quadrupole, dipole, and directional modes, respectively. The directivity plots include two ovals which show the array orientation. The driven pairs of transducers, whose sides are labelled A and B, are the gray-filled ovals, while the inactive pairs are represented by white ovals.

5.1 Cardioid from Separate Quadrupole and Dipole Elements

As in the conventional textbook problem, the principle of superposition for sound pressure was exploited using only the top two elements in the array. The top element was driven in its quadrupole (omnidirectional) mode and the second element was driven in its dipole mode. Both elements were driven at 810 Hz. As Fig. 14 shows, we obtained a cardioid pattern with a small backlobe. This result is simulated using Eq. (1) and (C_1, C_2, C_3)=(0.8, 1.2, 0) (see Fig. A8).

5.2 Cardioids from Element Pairs

Four cardioids oriented every 90° were produced by exciting adjacent pairs of transducer elements driven in their directional modes at 900 Hz. Figure 15 shows the measured patterns for the top two elements driven in the 0° direction (fore), and upon reversing the leads, driven in the 180° direction (aft). The bottom two elements were not driven. The two cardioids may be simulated using Eq. (1) with (C_1, C_2, C_3)=(1, 1, 0) (see Fig. A5) and (C_1, C_2, C_3)=(1, -1, 0), respectively.

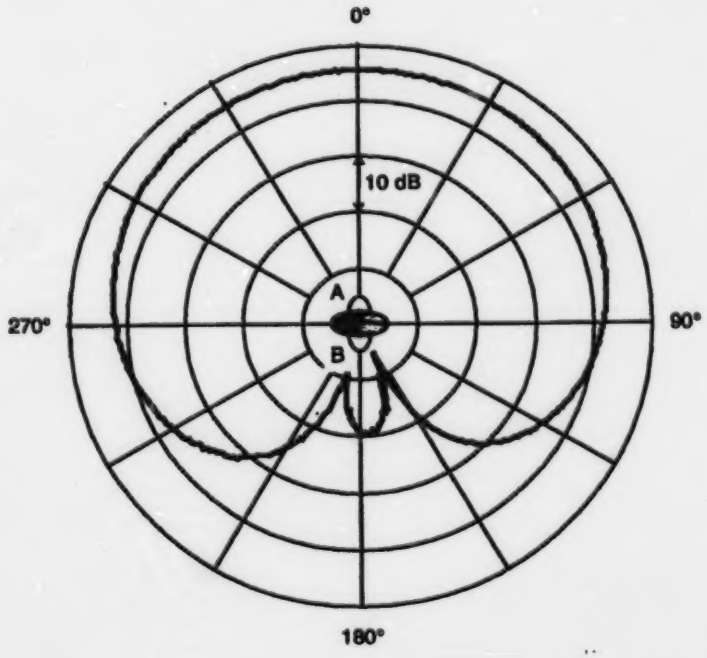

Figure 14: Directional beam from separate quadrupole and dipole elements at 810 Hz.

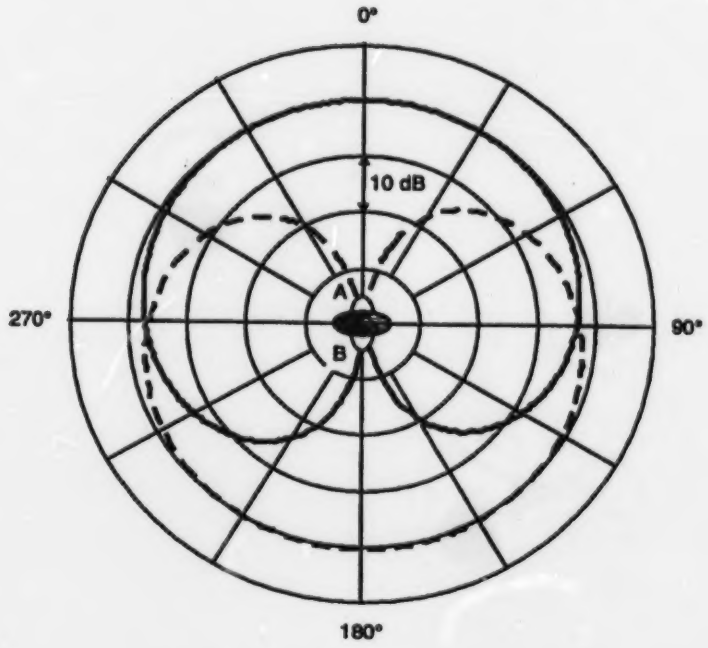

Figure 15: Fore/aft (solid/dashed) beams from top two elements at 900 Hz.

By exciting the bottom two elements in their directional modes at 900 Hz, we obtained the cardioids in Fig. 16. The top two elements were not driven. The cardioid in the 270° direction (left) can be simulated using $(C_1, C_2, C_3)=(1, 0, -1)$ while the cardioid in the 90° direction (right) can be simulated using $(C_1, C_2, C_3)=(1, 0, 1)$ (see Fig. A6).

Two directional elements spaced just under a half wavelength can now be compared to both the single element and the four-element ATAS array. For example, consider the solid curve in Fig. 16. The bottom two elements driven in their directional modes have a 70 dB left/right ratio and will produce a field-limited source level of 219 dB//1μPa-m. This source level exceeds that of the ATAS array by 2 dB. It is also 5 dB greater than the single directional element discussed in Subsection 4.3, a result that is consistent with the predicted half wavelength spacing improvement of 6 dB for two elements. These comparisons are summarized in Table 1.

Table 1: Directional mode performance comparisons.

Name	Number of Elements	Frequency (Hz)	Source Level dB//1μPa-m/V	Left/Right Ratio (dB)
ATAS	4	950	217	15
Class IV	1	900	214	44
Class IV	2	900	219	70

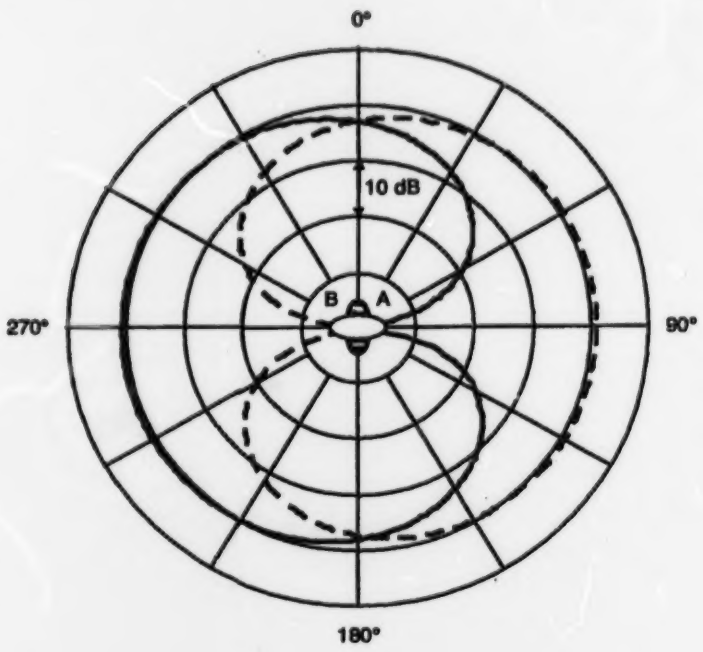

Figure 16: Left/right (solid/dashed) beams from bottom two elements at 900 Hz.

5.3 Four-Element Quadrupole Drive

When all four elements in the orthogonal array were driven in their quadrupole modes, the resulting horizontal directivity pattern was omnidirectional, as shown in Fig. 17. Since this non-directionality is independent of frequency in the band of interest, we obtained circular patterns at both 900 Hz and 1400 Hz. Upon closer inspection, we also noticed that the circles are nearly perfect in shape due to the orthogonal orientation of the two pairs of transducers. In fact, where the single element deviated from omnidirectionality by 2.3 dB (see Subsection 4.1), the four-element orthogonal array deviated by less than 0.5 dB. The pattern in Fig. 17, like that in Fig. 6, can be simulated using (C_1, C_2, C_3)=(1, 0, 0) (see Fig. A1).

By driving all four elements at 900 Hz in the quadrupole mode, a field-limited source level of 223 dB//1μPa-m is possible. This increase of about 13 dB in source level over that of a single element (see Subsection 4.1) is consistent with the factor 20 log 4 = 12 dB for a four-element array.

5.4 Four-Element Dipole Drive

By driving all four elements in their dipole modes, it is possible to generate another dipole at an angle of 45° based on the simulation (C1, C2, C3)=(0, 1, 1) (see Fig. A4). This was indeed found to be the case, as suggested by the patterns in Fig. 18 at both 700 Hz and 900 Hz. It is also a simple matter to orient these four-element dipoles at 135°.

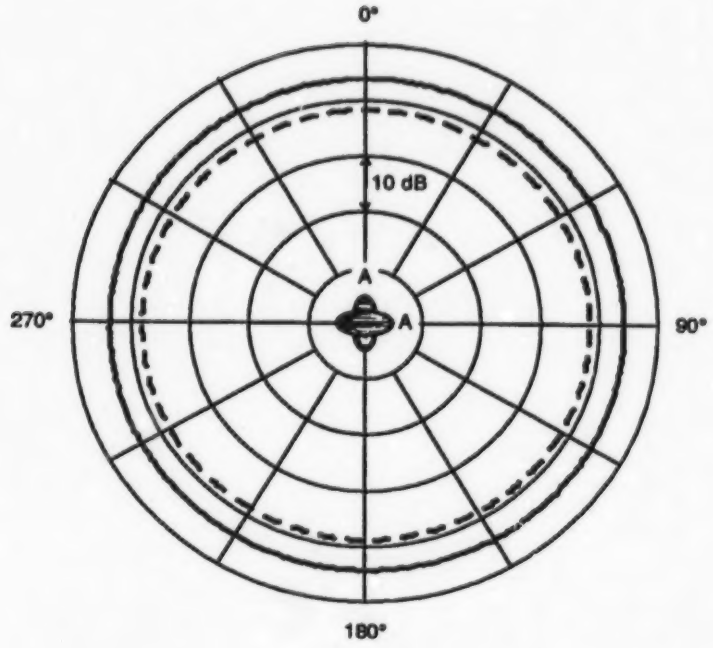

Figure 17: Four-element omni patterns at 900 Hz (solid) and 1400 Hz (dashed).

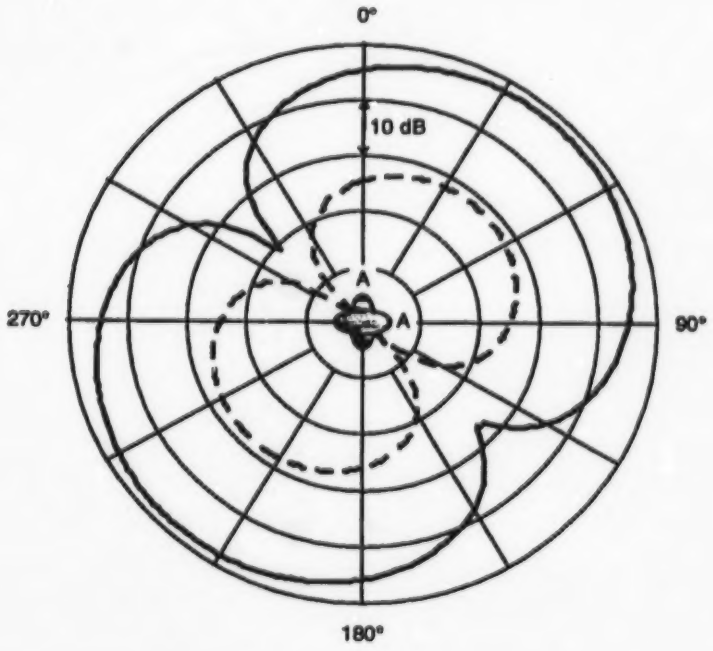

Figure 18: Four-element dipoles at 900 Hz (solid) and 700 Hz (dashed).

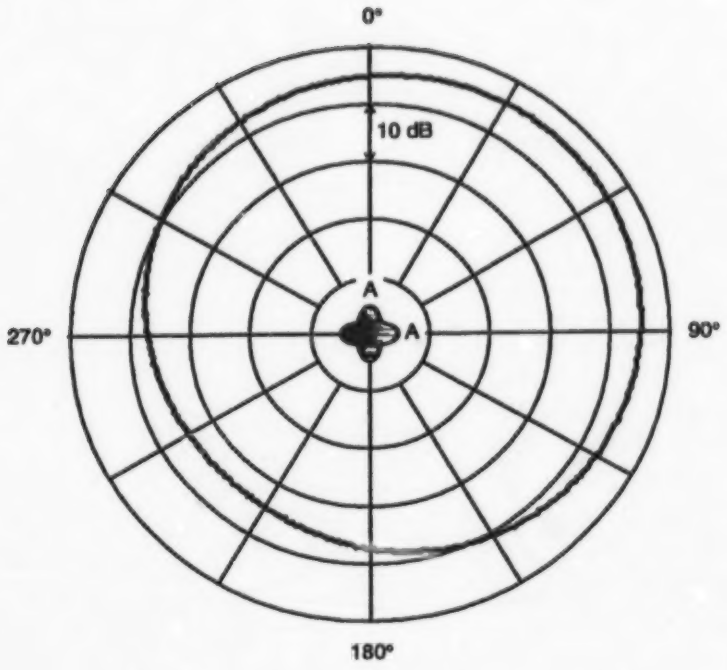

Figure 19: Four-element directional pattern at 900 Hz.

The excitation of all four elements gives a calculated field-limited source level of approximately 227 dB//1_Pa-m at the maximum radiation axis (45°) and 900 Hz. This is 8 dB more output than a single element and 4 dB more than a pair of elements at the same frequency in the same mode. The reason for not achieving an increase of 20 log 4 = 12 dB is because we are combining dipoles in quadrature.

5.5 Four-Element Directional Drive

Although time for our experiments at Seneca Lake was running very short, we were able to make one attempt at driving all four elements in the orthogonal array in their directional modes. From the simulation using Eq. (1) and (C1, C2, C3)=(2, 1, 1) (see Fig. A7), it was anticipated that we could obtain a cardioid at 45°. Figure 19 shows the resulting pattern at 900 Hz, which is qualitatively close to the pattern obtained from the simulation. The calculated field-limited source level at the maximum radiation axis (45°) is 224 dB//1_Pa-m, which is 10 dB better than a single element and 5 dB better than a pair of elements.

The parameter that was sacrificed by combining these directional modes in quadrature was the 45°/225° ratio (i.e., the "front/back" ratio), which is only 12 dB (cf. 44 dB for a single element and 70 dB for two elements in Table 1). It should be pointed out, however, that time constraints did not permit manual fine-tuning to obtain the best null possible, a procedure that was carried out for all of the other patterns. Finally, an improved ratio should also be achievable by using two additional elements in the array, by reducing the 90° angle between the element pairs, or both.

6. Conclusions

This paper presented the directivity pattern measurements for a low-frequency directional Class IV flextensional transducer and a four-element orthogonal array. The versatility of using directional array elements was illustrated by the omnidirectional, bidirectional, and unidirectional patterns produced by both the single element and the array. Since the single element can transmit left or right, the orthogonal array can transmit left, right, fore, aft, and at 45° intervals between these directions. In addition, the array produced a symmetrical omnidirectional pattern when all four elements were excited in their quadrupole modes due to the orthogonal array configuration. Although low voltage drive levels were used in these tests, the calculated source levels presented here are consistent with high power tests performed on these transducers in the past [11].

Areas of interest for further investigation are as follows: (1) simultaneous excitations of the left and right cardioids using two different frequencies; (2) measurements of the vertical beam patterns of the array; (3) optimization of the 45° unidirectional beams; (4) high power tests of the array; (5) evaluation of array performance using vibration isolation mounts for each element.

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Appendix

The measured directivity patterns for the directional Class IV flextensional transducer and the four-element orthogonal array can be simulated using Eq. (1) from Section 3, which is conveniently repeated here as follows:

$$P(\theta) \propto \left| C_1 + C_2 \cos(\theta) + C_3 \sin(\theta) \right|, \tag{A1}$$

where C_1, C_2, and C_3, are constants whose values determine the shapes of the patterns. A number of examples are given below.

Figure A1 is an omnidirectional pattern like those shown in Figs. 6 and 17. Figure A2 is a dipole pattern like the one shown in Fig. 10 and Fig. A3 is a dipole in quadrature. Figure A4 is the combination of these two dipoles, as shown in Fig. 18. The cardioid pattern in Fig. A5 is shown as the solid pattern in Fig. 15. Figure A6 is the cardioid shown as the dashed pattern in Fig. 16. The cardioid pattern in Fig. A7 is the sum of the previous two cardioids and is shown in Fig. 19. Finally, the cardioid pattern with a backlobe shown in Fig. A8 can be seen in Figs. 12 and 14.

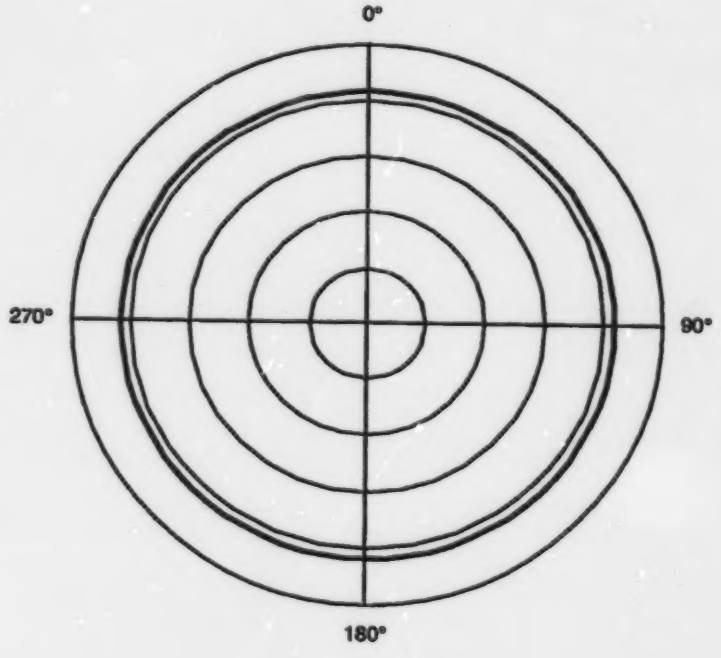

Figure A1: Omnidirectional pattern simulation (C_1, C_2, C_3)=(1, 0, 0).

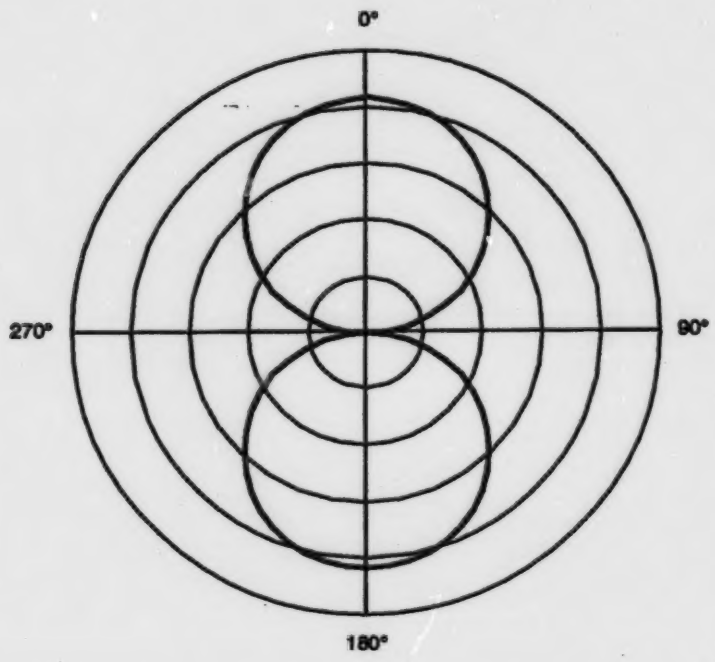

Figure A2: Dipole pattern simulation (C_1, C_2, C_3)=(0, 1, 0).

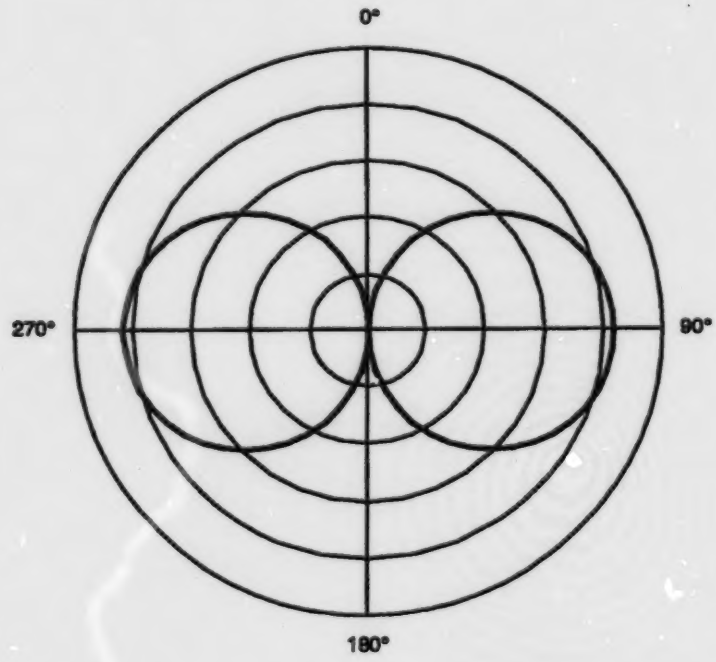

Figure A3: Dipole pattern simulation (C_1, C_2, C_3)=(0, 0, 1).

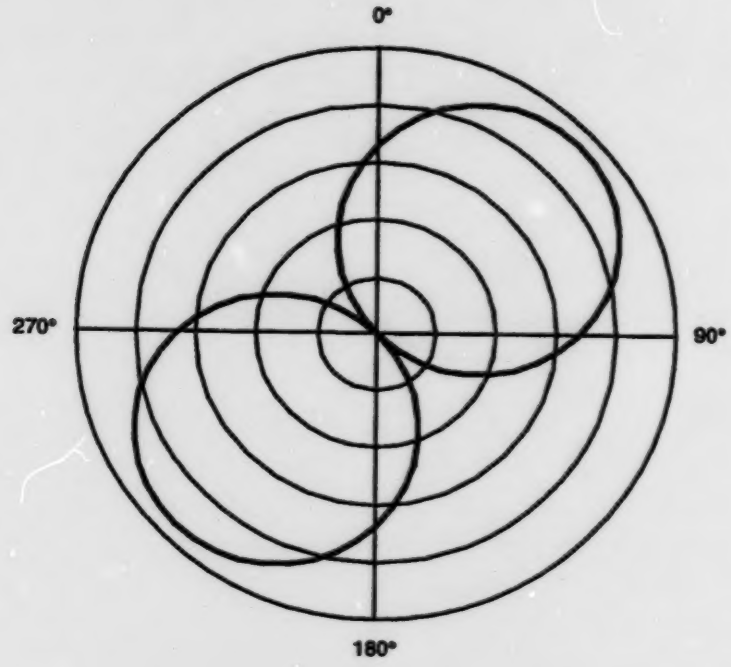

Figure A4: Dipole pattern simulation (C_1, C_2, C_3)=(0, 1, 1).

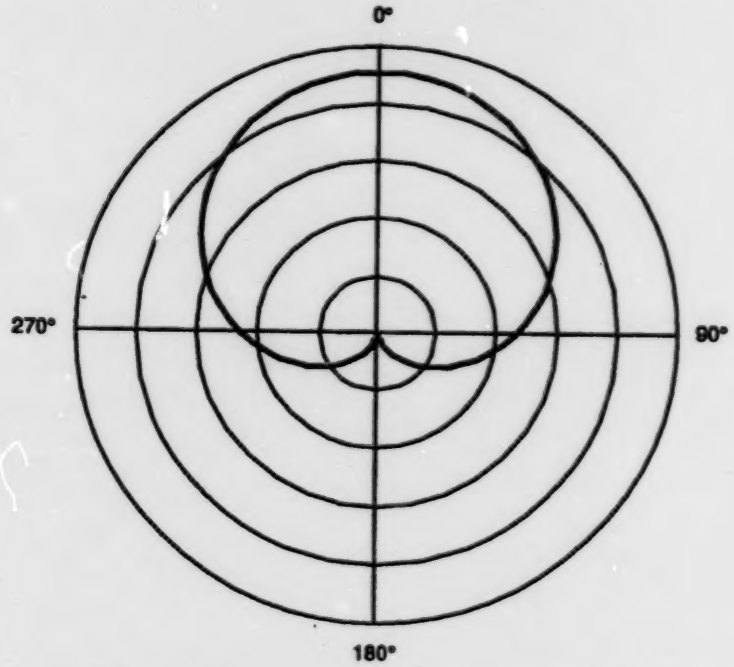

Figure A5: Cardioid pattern simulation (C_1, C_2, C_3)=(1, 1, 0).

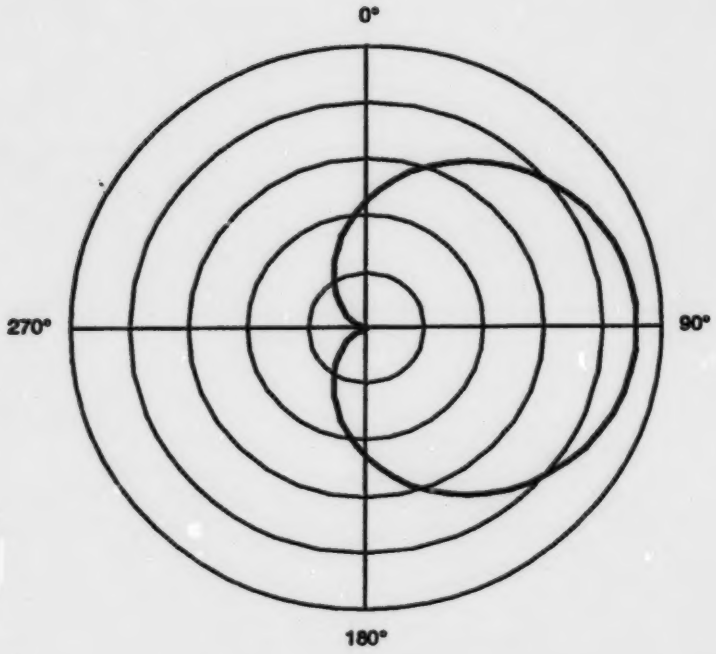

Figure A6: Cardioid pattern simulation (C_1, C_2, C_3)=(1, 0, 1).

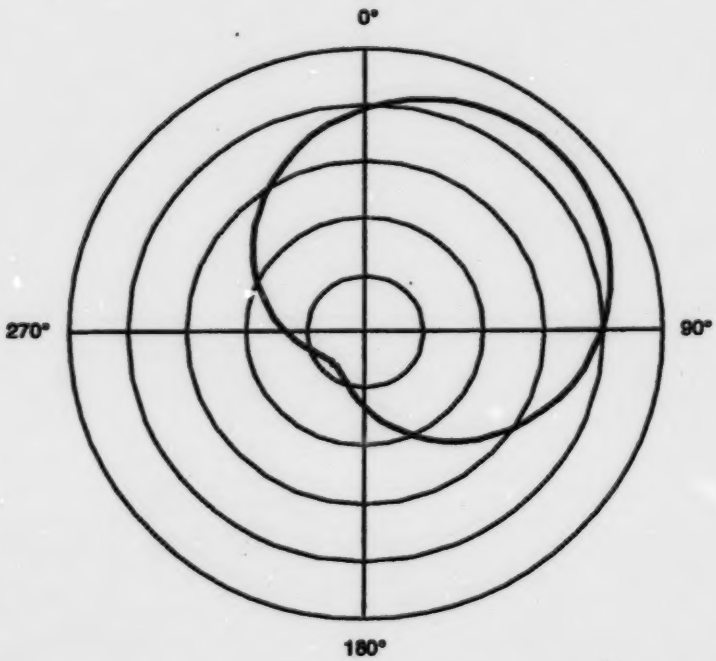

Figure A7: Cardioid pattern simulation (C_1, C_2, C_3)=(2, 1, 1).

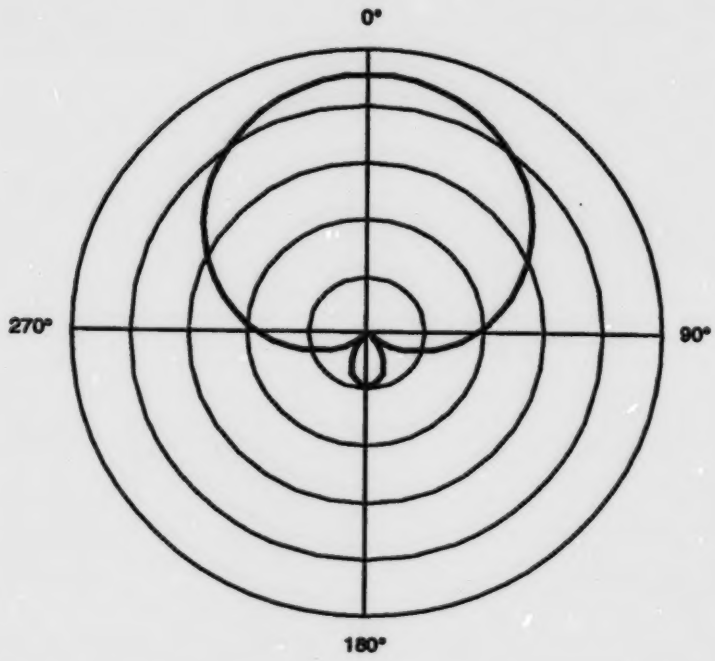

Figure A8: Cardioid with backlobe pattern simulation (C_1, C_2, C_3)=(0.8, 1.2, 0).

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Acoustic monopoles and the principle of superposition (applied to sound pressure) are fundamental tools that can be used to construct theoretical dipole and cardioid sound sources. Strictly speaking, the size of these monopoles, and their separations when forming simple multipoles like dipole doublets, must be small compared to the wavelengths emitted. In the practical field of sonar transducer design, however, transduction devices have finite dimensions, and consequently, do not meet the basic size and separation criteria for their transmissions to be accurately described by those of multipole sources. Nevertheless, there are transducers that produce good approximations to the omnidirectional, bidirectional, and unidirectional radiation patterns of monopole, dipole, and cardioid sources, respectively. One such device is the low-frequency (900 Hz) directional Class IV flextensional transducer. A single element alone can produce omnidirectional, dipole, and left/right cardioid patterns. This unique capability provides the array designer with many options for generating directional beams, compared to arrays composed solely of omnidirectional sources. In this work, the directivity patterns of a single Class IV element and a four-element orthogonal array are presented. A simple theoretical expression based on multipole sources and the principle of superposition is put forward to qualitatively explain all of the measured patterns. [Work supported in part by the Office of Naval Research]

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